Reply to Kasperski, Kuchinskaya and Josephson on "J-value assessment of relocation measures following the nuclear power plant accidents at Chernobyl and Fukushima Daiichi" by I. Waddington, P. J. Thomas, R. H. Taylor, and G. J. Vaughan

We thank Kasperski *et al*. for their interest in the "Relocation Paper" of Waddington *et al*. (2017) and for voicing concerns that may well have been at the back of many people's minds before the NREFS Special Issue was published.

Kasperski *et al.* (xxxx) argue in favour of a universal policy of relocation after a big nuclear reactor accident even where the risk posed to the public by the radioactive fallout is small, saying:

> "The point is that there will always be a degree of uncertainty that should lead to such precautionary measures as evacuation even if it turns out that risk was exaggerated."

Hence Kasperski *et al.* disagree with the use of the J-value in the "Relocation Paper" of Waddington *et al*. (2017), which suggests that the relocation of fewer than a quarter of the 335,000 people actually moved away permanently (or "relocated") could be justified after the Chernobyl accident. Meanwhile the J-value recommended that the 160,000 people moved away after the accident at Fukushima Daiichi ought to have been allowed to remain in their homes, given the Japanese Government's 20 mSv per year safe return dose.

Their argument against the J-value turns out to be part of their more general philosophy, as Kasperski *et al.* believe that it is not possible to apply quantitative methods as a guide to human behaviour:

> "The use of the quantitative methodologies of necessity ignores issues that cannot be quantified"

and

> "To put it simply, technological tools to consider technical costs, benefits and risks, exclude the human factor."

We have a degree of sympathy with this position, to the limited extent that we concur that modelling human behaviour is indeed a difficult task. For example, two of the authors of the Relocation Paper have been highly critical previously, in the pages of this journal, of attempts to quantify the "value of a human life (VPF)" in the UK, showing that the approach employed was so flawed as to lose any validity (Thomas and Vaughan, 2015). See also (Thomas and Vaughan, 2014). However, to reject all technological tools would be to reject such useful mathematical constructs as game theory (von Neumann and Morgenstern, 1944) and, indeed most, if not all, of economics, as well as the J-value. We have to disagree with this stance.

Before the J-value was devised, techniques existed to estimate the probability of an accident happening in the nuclear industry and others, as well as the number of people likely to killed if it did. The Reactor Safety Study (US NRC, 1975) constitutes an early example. It was even possible, in a more sophisticated approach, to calculate the loss of life expectancy in the population under threat after a big nuclear accident (Marshall *et al*., 1983). But given a non-zero probability of serious harm, the question remained: how does one judge how much ought to be spent to reduce the likelihood further? Stopping all activities involving any degree of risk is ruled out by the fact that there is a level of risk associated with everything we do. Living is an inherently risky business, whether one ventures out and braves being knocked down by a car or stays inside one's house to face a multitude of domestic hazards (electrocution, falling down the stairs, death from fire and so on). Clearly less should be spent to counter a low risk and more for a high risk, but how does one decide how much? A comparative approach was often taken in the past, but this was open to the significant problem that, historically, very different sums of money have been devoted to averting similar levels of harm (Tengs *et al*., 1995). Cost-benefit analysis applied to situations involving the possible curtailment of life relied in the UK, at least, on a VPF figure dependent on only a small number of opinions assembled within an invalid framework for interpretation, as noted above.

The J-value method (Thomas *et al*, 2006a,b,c), based on the Life Quality Index (Nathwani, 1997, Nathwani *et al*., 2009), allows an objective balance to be struck for the first time between what is spent on safety and the benefit that will be achieved. The method has been validated against pan-national data on the revealed preferences of literally billions of people all over the world (Thomas and Waddington, 2017, Thomas, 2017a). It is this combination of objectivity and empirical validation that constitutes the J-value's unique attraction for conducting cost-benefit analyses to assess the correct level of spending to reduce a threat to human life. It allows both balance and consistency to be extended to safety decisions where people may have less of an historic feel for the level of risk, as in the case of nuclear radiation.

If other socio-political factors are to alter public decisions away from the baseline provided by the J-value, these should set out explicitly and transparently to justify why the hazard in question should be treated differently from other risks of similar magnitude.

As noted in the Discussion (Section 7) of the Relocation Paper, precautionary, temporary evacuation might be a reasonable response while the extent of a reactor release was being established. But the purpose of the Relocation Paper was to analyze the policy of evacuating members of the public for a long period or permanently after the accidents at Chernobyl and Fukushima Daiichi. The J-value analysis of relocation was conservative, as it took no account of the psycho-social impact (known to be heavy), which would militate further against moving out large numbers of people long term. Section 7 reviews evidence of likely damaging effects.

Kasperski *et al*. suggest in their second last paragraph that a chaotic response to a big nuclear accident is inevitable. We have to disagree. As noted in the Relocation Paper, the availability, in advance of any accident, of

- "spatially distributed, real-time measurements of ground contamination (an innovation that modern technology could make viable)
- "a prediction model for current and future dose such as the MIB [Moscow Institute of Biophysics] model
- "a model to convert dose into loss of life expectancy such as CLEARE, and
- "a J-value program to provide evolving J-value guidance

"would allow decision makers to make sensible judgements on who should be evacuated on a temporary basis. The number of people asked to leave their homes if only for a short time could then be minimised so as to keep disruption to a minimum."

Detailed points

Paragraph 2 of Kasperski *et al*. Concerning radiological data, documents produced by the UN Standing Committee on the Effects of Atomic Radiation (UNSCEAR, 2015 sets out its guiding principles), the Moscow Institute of Biophysics model and data from the European Commission report from Lochard and Schneider formed the basis for the J-value assessment of the 1st Chernobyl relocation of 116,000 people in 1986 and the 2nd relocation of 220,000 four years later. Sensitivity studies were carried out, including the 95th percentile case, where entire settlements would be evacuated if 5%

of the population merited relocation. While there will, inevitably, be scope for inaccuracy in both the measurements and the model, confidence in the results is generated by the commonality in the overall conclusions coming from the other two, diverse approaches used in the NREFS project (Managing Nuclear Risk Issues, Environmental, Financial and Safety); these were optimal economic control (Yumashev *et al*., 2017) and PACE-COCO2 (Ashley *et al*., 2017).

Paragraph 3. The life quality index is proportional to the utility of earnings rather than to the earnings *per se*. The chosen measure of average earnings, GDP per head, is an ethical choice that allows the next day of life for each person in the nation to be valued the same.

Paragraph 4. Contrary to the claim of Kasperski *et al.* that we "ignored the dosages received" and the "uncertainty of their distribution", the doses in each settlement were based on UNSCEAR documentation. Moreover, detailed allowance was made for the distribution of dose within each township, as explained in Appendices A, B and C.

Paragraph 5. In promoting a wise choice of safety measures, the J-value method takes account of the resources available to those living within a nation. This is how it is able to explain the shape of the Preston curve of life expectancy at birth versus GDP per head. The Relocation Paper examined two nuclear accidents, one in the wealthy country of Japan (2011) and one in the USSR (1986), which, as Kasperski *et al.* point out, was not wealthy by world standards. We presented full details of the J-value calculations in each case. Meanwhile, in companion papers, Ashley et al. (2017) considered a hypothetical major accident at a generic, modern water-cooled reactor in the UK, while Yumashev et al. (2017) consider the effects of hundreds of notional severe accidents at reactors sited in diverse economies across the world.

Paragraph 6. As Kasperski *et al.* note, the effects of radiation on humans have been studied by the International Committee on Radiological Protection (ICRP) for the past 90 years. Members of the public living in the vicinity have faced low-level radiation exposure after the world's two big reactor accidents. It is indeed a non-trivial task for the ICRP to separate out the effects of low-level radiation against the confounding background of life's other hazards. But all the years of study mean that we are probably closer to a reasonable answer on the effects of radiation than for most other pollutants. We would obviously reject firmly any imputation that the Relocation Paper might have recommended keeping people in place longer so as to enhance the gathering of radiological data.

Paragraph 7. It became possible in 1997 to make a first estimate of the likely number of childhood thyroid cancer victims caused by the Chernobyl accident (Thomas, 1997). Further epidemiological data to the end of 1998 allowed a better prediction (3300 – 7600) of the eventual number and the mean latency period, calculated as 17 years with standard deviation of 10 years. The large spread about the mean accounts for the fact that cases could start coming to light within 4 years of the accident (Thomas and Zwissler, 2003). Exposure to ^{131}I (half-life 8 days) and possibly other, shorter-lived iodine isotopes, is the most likely cause of the thyroid cancers observed, with a prior iodine deficiency in the area a further contributing factor. The approximately 7,000 cancers recorded after Chernobyl, while undoubtedly of concern, are susceptible to medical treatment leading to full remission in about 98% of cases. Early use of prophylactic iodine is the established mitigation measure. By contrast, relocation will be rather ineffective because it is inherently slow and unlikely to be completed until the radioactive iodine has decayed to negligible levels and the threat has subsided.

Paragraph 8. This paragraph seems to reject scientific principles and the possibility of using a scientific model to calculate a future outcome. We do not agree.

Paragraphs 9 and 10. The Relocation Paper reviewed the results of the Lochard and Schneider (1992) study as an important contribution to the prior literature. But the J-value method represents a significant theoretical and practical advance, as was emphasized in the comments in the relevant section 4.1 of the Relocation Paper that discussed the Lochard and Schneider work. To be clear: the results of the Relocation Paper do not rely on the results of the analysis by Lochard and Schneider.

Paragraphs 11 and 13. The comments of Kasperski *et al*. on the health consequences of radiation exposure are similar to the concerns they expressed in their paragraph 6, to which we have responded above. Their suggestion that the authors of the Relocation Paper have "chosen cost as their standard" is misleading. The J-value balances life expectancy gained against the cost of the safety measure using an objective and empirically validated method. The benefit is judged by reference to the satisfaction or utility that the people affected can expect to gain over the rest of their lives: overspending on safety will diminish people's utility.

The J-value, with its emphasis on life expectancy, can extend the way that people decide on life prolonging measures to those safety decisions where, for a variety of reasons including unfamiliarity with the hazard, people have less of an intuitive feel for the level of risk. Nuclear radiation is an obvious example. The fact that the J-value has been validated against empirical data (Thomas and Waddington, 2017) increases confidence that the J-value will yield reasonable results. It will also give consistency, irrespective of the industry concerned (nuclear, chemical, rail transport, health etc.). Moreover the J-value can be argued to embody the principle of "reasonable achievement" in the sense that it identifies the amount of resource that people in the nation would normally want to devote to reducing a risk of the specified magnitude.

Paragraph 12. The paragraph seems inimical to the development and application of measurement science. By contrast, we would contend that scientific instruments, no less in the field of radiation than in other fields, allow the acquisition and development of further knowledge that can help mankind.

Paragraph 14. The reactor at Chernobyl was contained during normal operation within individual pressure tubes inside a reinforced concrete cavity. The severe accident it suffered caused this containment to be breached catastrophically, as explained. No suggestion was made or implied that there was a reactor containment building at the Chernobyl nuclear power station comparable to that used in a Western-designed Pressurized Water Reactor. For fuller details see World Nuclear Association (2016 and 2018).

Paragraph 15. The Relocation Paper was concerned with applying the J-value to assess the relocation measures instituted after the world's two largest nuclear reactor accidents, which occurred at Chernobyl in 1986 and at Fukushima Daiichi in 2011. Kyshtym formed part of the Soviet Union's military rather than its civil nuclear programme; the accident was classified by the IAEA as less severe than those at Chernobyl and Fukushima Daiichi (Britannica, 2017). The authorities did not recommend relocation after the 1979 accident at Three Mile Island (Stallings, 1984).

Paragraph 17. Despite recommending a policy of mass evacuation after every nuclear reactor accident, Kasperski *et al*. argue that such a course of action will always result in chaos. By contrast, the Relocation Paper points to the provision and interpretation of better measurement data, provided in real time, as a way of ensuring orderly control of the post-accident situation. Such information could be provided not only to the incident controller but also to politicians, the media and the general public (Thomas, 2017b). Regularly updated predictions could be provided for the loss of life expectancy resulting from living in the towns and villages in the vicinity of the nuclear plant for the next 70 years or more, figures likely to be reassuring in many cases. For example, based on contamination data taken after fallout deposition had finished following the accident at Fukushima Daiichi, the average radiation-induced loss of life expectancy in Tomioka Town could be estimated as less than 3 months. Tomioka was, in fact, the worst affected settlement after the accident at Fukushima Daiichi.

We hope that these responses will promote a better appreciation of the paper's key message, shared with the other two, diverse methods applied in the NREFS project, which is that relocation of people following a big nuclear accident is a policy measure to be used sparingly if at all.

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